A FEMTOSECOND ALL-FIBRE COMPRESSOR

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Received 18 May 1987

An all optical fibre pulse compressor operating in the femtosecond regime is presented for the first time. Coexisting with 100 ps pulses from a cw mode locked Nd:YAG laser operating at 1.3 μm, pulses of 130 fs were generated in a standard single mode fibre through a single pass multi soliton Raman compression. These pulses were further compressed in a two stage dispersion shifted fibre arrangement. Pulses as short as 65 fs were generated.

Optical pulse compression using a conventional single mode optical fibre-grating pair configuration has proven to be a highly versatile technique in the generation of picosecond and femtosecond pulses over a wide spectral range [1–6]. At wavelengths below the dispersion minimum of the fibre, the technique is based on the compensation of the dispersed, self phase modulated induced chirp, experienced on propagation through the positively dispersive fibre, by the negative dispersion of the grating pair. How-
ever, the negative dispersion can be applied by other means [7–9]. The simplest and most elegant means now of self compression is to operate at laser wavelengths above the fibre minimum dispersion, the region of anomalous dispersion. In this regime self-phase modulation broadening and group velocity dispersion compression can give rise to self sus-
tained propagating pulses, solitons, as proposed by Hasagawa [10] and first observed by Mollenauer et al. [11]. Depending on the experimental parameters the soliton in the initial regions of the fibre can be of constant pulse width or can compress. Recently, Blow et al. [12] by selection of the laser wavelength and the use of dispersion shifted fibres, first dem-
strated experimentally in the picosecond regime (~100 ps), the use of a dispersion shifted fibre as the negatively dispersive element in a two-fibre cascade pulse compressor arrangement.

In this letter we report on the compression of the pulses derived from a single pass soliton-Raman interaction in a standard single mode fibre, to optimised durations of 65 fs by means of an all optical fibre compressor arrangement.

The experimental scheme is shown in fig. 1. A cw mode locked Nd:YAG laser (a modified Quantro-

nix model 116), which has been described in detail previously [13], was used as the fundamental source of pulses at 1.32 μm. It is sufficient to note that it generated 90 ps pulses at a 100 MHz repetition rate, with an average power of 1.8 W. This was coupled, using an uncoated ×20 microscope objective, with 50% efficiency, into a standard single mode at 1.32 μm, non polarization preserving optical fibre (Fp), which had a dispersion minimum in the region of 1.32 μm. The role of this first fibre is as an efficient Raman generator. Through pumping at 1.32 μm, the Stokes Raman amplified radiation lay in a region of anomalous dispersion, hence permitting soliton evo-
uation [14] at these wavelengths. Through multisoliton-Raman generation, it is possible to generate highly temporally compressed, stable trains of pulses with a bandwidth extending from just above 1.32 μm to beyond 1.45 μm. The generated soliton-Raman pulse width is a function of the fibre length and peak pump pulse power for a fixed pump pulse width. A complete characterisation of the single-pass soliton-Raman pulse generation system has been submitted elsewhere [15]. Typically for a 300 m fibre (Fp) length, with 800 mW average pump power, 130 fs
pulses with high amplitude stability (<1% fluctuation) and 400 mW average power in the Raman band were generated. Fig. 2 shows a "real time" trace of a scanning background free autocorrelation trace taken over a long exposure time, clearly indicating the high stability of the 130 fs soliton Raman pulses.

A non-soliton component of the compressed pulse was present as a pedestal on the autocorrelation. This component was dependent on the experimental parameters of fibre length and pump power [15]. For the case of F1 ~ 300 m, only 10% of the output energy was in the 130 fs soliton pulse, corresponding to a peak power of ~ 3 kW. The autocorrelation traces indicated that the background extended for ~ 120 ps and occupied approximately one tenth of the autocorrelation signal intensity. By using polarization selection however, it is possible to reach the situation where the broad non-soliton component could be rejected [15, 16], although, in the experiment described here this was not carried out, and would be best applied after the third fibre stage.

Using a filter (f) the fundamental radiation was removed and the transmitted soliton-Raman signal was focussed into the fibre F1, the first stage of an all fibre compressor. This fibre was nonpolarization preserving, single mode at 1.32 μm with an effective 6 μm core diameter, a loss of < 1 dB/km and a dispersion minimum wavelength at 1.55 μm [17]. At 1.4 μm the group velocity dispersion due to self phase modulation gives rise to a positive frequency chirp, as in the case of a conventional fibre–grating pair compressor, consequently the soliton-Raman pulse generated in the first fibre experienced purely dispersive broadening temporally and self phase modulated spectral broadening.

The negatively dispersive element of the compressor, fibre F2, was again non-polarization preserving, single mode at 1.32 μm, with a core diameter of 9 μm, a dispersion of -11 ps/km nm at 1.4 μm and a zero dispersion wavelength at 1.275 μm [18].

Coupling into and out of the fibres was achieved using uncoated microscope objectives and the pulsewidths on exit from each fibre stage of the compressor was examined using a background free autocorrelation technique, with a temporal resolution of better than 20 fs. An overall average power coupling efficiency for each stage (fibre and microscope objectives) of approximately 25% was typical.

For fixed input parameters of peak power and pulsewidth there exists for any particular wavelength an optimum fibre length Zcyc of fibre F2 to achieve maximum compression in the compressor [19]. For our particular fibre parameters and input pulses, a fibre length of 0.5 m was predicted, with a compression ratio of times two. Experimentally, with a fibre length F2 of less than 1 m very little overall compression could be achieved. It was found empirically that in
the situations where the input pulse experienced a temporal broadening of approximately 3 to 4 times then compression could be achieved. For a fibre length $F_1$ of 3 m the required broadening was obtained. In determining the optimum theoretical fibre length of a fibre compressor [19] it is assumed that the pulses entering the system are transform limited. However in the case of the single pass soliton-Raman pulses, this situation is far from being observed and an obvious chirp exists on the pulse [15]. In the case of Raman generation the form of the chirp can take quite a complicated form, and a fibre length different from the theoretical optimum would be expected. Typically, the spectral width ($\Delta \nu$) of the 130 fs pulses in the first fibre was 160 nm, which if transform limited at 1.4 $\mu$m is capable of supporting 13 fs pulses and indicates the large departure from transform limited operation and the degree of chirp on the pulses.

The degree of negative group delay required to compress the chirped pulses exiting fibre $F_1$ was also determined experimentally. Theoretically, the compression would require diffraction grating separation of several millimeters, which is equivalent in dispersion to a fibre of the order of a meter. The optimization was carried out as a "cut back" experiment on fibre $F_1$, initially several meters long, for several input pulse parameters. The result of this can be set in fig. 3. For a fibre length $F_1$ of 500 m, the soliton Raman pulse width was 180 fs at an average pump power level of 700 mW. Fibre $F_2$ was maintained at 3 m and at a fibre length $F_3$ of 2 m a minimum in the overall compressed pulse width of 120 fs was obtained. Above and below this length for fibre $F_2$, the overall compression width increased. Similarly, with $F_1$ at 300 m, the soliton Raman pulse width was 130 fs and $F_2$ optimised around 4 m, with an average power in the pulses of 40 mW. Fig. 4 shows the autocorrelation traces obtained at each stage of the compression process. The soliton Raman pulse of 130 fs is shown in fig. 4(a) which broadened to 520 fs (fig. 4(b)) in 3 m of fibre $F_2$, while fig. 4(c) shows the autocorrelation of the finally compressed 65 fs pulse representing an overall compression of times two. However, not all the average power was contained in the compressed pulse. The original pedestal on the input soliton pulse was in evidence, and the compressed pulse contained only 10% of the average power, which represents a peak power in the 65 fs pulse of 1 kW. However, as noted before, experimental techniques utilizing intensity dependendent polarization effects in fibres [16,20] could be used to reduce the pedestal.

In conclusion, we have demonstrated for the first time an all fibre pulse compressor operating in the femtosecond regime, and optimized the system for various input parameters. The degree of pulse compression agreed relatively well with theoretical prediction, although the input pulses were quite strongly chirped. Peak powers in the region of 1 kW were obtained in the optimum compressed 65 fs pulses and should be a useful source for nonlinear optical studies. By fusing the fibres together in cascade, rather than lens coupling, higher average powers and possibly higher compression ratios may be achieved. The technique can be generally used for all bands covered by the Raman generation process and in principle, by using fused fibres, a completely lossless system could be obtained, and has the considerations of cost and simplicity in its preference to a grating technique. In addition with reduced pulse widths now available from the initial single pass
soliton Raman source [15] even shorter pulses should be available from the compressor.

The major funding for this work by British Telecom Research Laboratories, Ipswich, England is gratefully acknowledged as is a contribution from the Science and Engineering Research Council. A.S. Gouveia-Neto is supported by a studentship from CAPES, a Brazilian Agency. Extended financial sup-
port to A.S.L. Gomes from CNPq, a Brazilian Agency, is also gratefully acknowledged.

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